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Duke University
2200 W Main Street
Suite 710 Erwin Square
Durham, NC 27705 -4677

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14. ABSTRACT
Nearly all military operations require remote power. For instance, consider the modern soldier who has been equipped with an increasingly sophisticated array of sensing, communications, and related electronics. While batteries have historically been used to power these electronics, alternative solutions are now required since a significant number of batteries, along with their increased weight, must be carried to meet the power requirements of short-term missions. Scavenging energy from the ambient environment, to either replace or recharge batteries, is

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Report Title

Final Report

ABSTRACT

Nearly all military operations require remote power. For instance, consider the modern soldier who has been equipped with an increasingly sophisticated array of sensing, communications, and related electronics. While batteries have historically been used to power these electronics, alternative solutions are now required since a significant number of batteries, along with their increased weight, must be carried to meet the power requirements of short-term missions. Scavenging energy from the ambient environment, to either replace or recharge batteries, is one of the most promising strategies for meeting the power requirements while simultaneously reducing the weight load. However, energy harvesting has yet to reach its full potential because the past works have narrowly focused on frequency matching to achieve linear resonance.

To summarize, the current state of the art in mechanical energy harvesting is ineffective for many environments. The proposed research explores new concepts with the potential to offer fundamentally new insights for energy harvesting. I expect this project to provide enabling technological advancements, with outcomes that are applicable to numerous defense applications, while simultaneously providing general scienti?c insights targeted to supplant the current design paradigms.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Detailed listing of publications is given in an attached document

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

• Philip E Doak Award - Journal of Sound and Vibration. Awarded for the most cited journal article over a four year period.

• Elected Fellow of the American Society of Mechanical Engineers, Jan. 2013

• Selected for an endowed professorship. I was appointed as the Jeffrey N. Vinik Associate Professor of Mechanical Engineering and Materials Science as of July 1, 2012.

• Invited to give a plenary lecture on the topic of Nonlinear Energy Harvesting at the 2012 ASME SMASIS conference.

• Bernard, B.P., Mann, B.P., 2013, "Energy absorption in a 1D array of axially aligned pendulums with linear torsional coupling," Proceedings of the ASME International Mechanical Engineering Congress and Exposition, San Diego, CA, Nov. 15–21, paper no. IMECE2013-64470. - Best student paper award.

• Tweten, D.J., Mann, B.P., 2012, "Parameter identification of a nonlinear beam energy harvester," Proceedings of ASME Design Engineering Technical Conference, Chicago, IL, Aug. 12-15, paper no. DETC2012-70190. - Best student paper award.

• Stanton, S.C., Erturk, A., Mann, B.P., Inman, D.J., 2010, "On the manifestation and influence of material nonlinearity in electroelastic power generator" ASME/AIAA Conference on Smart Materials, Adaptive Structures, and Intelligent Systems, Philadelphia, PA, Sep. 29–Oct. 1 (Best student paper for the entire conference).

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Brian Bernard	0.25	
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Brian Mann	0.10	No
FTE Equivalent:	**0.10**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Ben Owens	
Brian Bernard	
Samuel Stanton	
Total Number:	**3**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

In contrast to the current state of the art, my research investigated using highly nonlinear interactions to obtain a more broadband response and to enable semi-active tuning. For instance, I will investigate different types of nonlinear restoring forces, both smooth and non-smooth forces, to adapt and/or tune the harvester's response to the environmental excitation, e.g. to trigger attractor escapes and/or the system to jump to a more energetic response. The general idea is to destabilize the local attractor, while keeping the global dynamics bounded, to harvest energy from the oscillations of a system that is transitioning between multiple states of equilibria. Since any nonlinear harvester can have multiple (co-existing) steady-state behaviors, I will investigate the selection of the desired response (attractor selection) from a momentary feedback perturbation; this idea, in contrast to a consistent control effort, which continuously dissipates energy, only perturbs the system once to trigger an attractor escape and cause the system to jump to a more energetic response indefinitely.

The final research phase explored a new concept where nonlinearity could be exploited in a beneficial fashion. More specifically, the creation of bandgap structures that passively reconfigure, in a prescribed manner, can provide enabling capability, e.g. the ability avoid damage in many structures. This threshold-triggered (or passively switched) type of response behavior would allow energy to be passed in a frequency band until the bifurcation parameter reached a critical value; once the bifurcation parameter exceeds this threshold, the bandgap structure would then reconfigure to attenuate energy propagation over a desired frequency range. In essence, the bifurcation point, bandpass, and bandgap regions must be simultaneously designed to achieve the aforementioned phenomenon (see Attachment for further details).

Technology Transfer

We have worked with program director Samuel Stanton to identify an ARL research group with compatible interest. A student on this project, Ben Owens, interviewed with this group at Redstone Arsenal and was hired for the summer of 2012 at AMRDEC.

Nonlinear Interactions for Broadband Energy Harvesting

A progress report submitted to:

Army Research Office

Program Officer: Dr. Ralph Anthenien
Research Area: Mechanical Sciences
Subcategory: Structures and Dynamics

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by

Principal Investigator

Brian Mann
Associate Professor
MEMS Department
238 Hudson Hall
Duke University
Durham, NC 27708
Tel: 919-660-5214
Email: brian.mann@duke.edu

Summary

Nearly all military operations require remote power. For instance, consider the modern soldier who has been equipped with an increasingly sophisticated array of sensing, communications, and related electronics. While batteries have historically been used to power these electronics, alternative solutions are now required since a significant number of batteries, along with their increased weight, must be carried to meet the power requirements of short-term missions. Scavenging energy from the ambient environment, to either replace or recharge batteries, is one of the most promising strategies for meeting the power requirements while simultaneously reducing the weight load. However, energy harvesting has yet to reach its full potential because the past works have narrowly focused on frequency matching to achieve linear resonance.

To summarize, the current state of the art in mechanical energy harvesting is ineffective for many environments. The proposed research explores new concepts with the potential to offer fundamentally new insights for energy harvesting. I expect this project to provide enabling technological advancements, with outcomes that are applicable to numerous defense applications, while simultaneously providing general scientic insights targeted to supplant the current design paradigms.

In contrast to the current state of the art, I propose to use highly nonlinear interactions to obtain a more broadband response and to enable semi-active tuning. For instance, I will investigate different types of nonlinear restoring forces, both smooth and non-smooth forces, to adapt and/or tune the harvester's response to the environmental excitation, e.g. to trigger attractor escapes and/or the system to jump to a more energetic response. The general idea is to destabilize the local attractor, while keeping the global dynamics bounded, to harvest energy from the oscillations of a system that is transitioning between multiple states of equilibria. Since any nonlinear harvester can have multiple (co-existing) steady-state behaviors, I will investigate the selection of the desired response (attractor selection) from a momentary feedback perturbation; this idea, in contrast to a consistent control effort, which continuously dissipates energy, only perturbs the system once to trigger an attractor escape and cause the system to jump to a more energetic response indefinitely.

Research Progress

Amplitude Filtering Through Bifurcation Induced Bandgap Changes - This tasks explored a new concept where nonlinearity could be exploited in a beneficial fashion. More specifically, the creation of bandgap structures that passively reconfigure, in a prescribed manner, can provide enabling capability, e.g. the ability avoid damage in many structures. This threshold-triggered (or passively switched) type of response behavior would allow energy to be passed in a frequency band until the bifurcation parameter reached a critical value; once the bifurcation parameter exceeds this threshold, the bandgap structure would then reconfigure to attenuate energy propagation over a desired frequency range. In essence, the bifurcation point, bandpass, and bandgap regions must be simultaneously designed to achieve the aforementioned phenomenon, as shown in the example case study below.

While we expect to explore numerous magnetic lattices arrangements with bandgap structures that can passively reconfigure, the present discussion will focus on the example of Fig. 1. This system has two masses in a unit cell, linear interconnections (assumed for simplicity, but not required), and a nonlinear restoring force for every other oscillator. Mathematically, this system can be described by the following two equations:

$$m_j\ddot{x}_j + d\,\dot{x}_j + k\left(2x_j - x_{j+1} - x_{j-1}\right) = 0 \qquad \forall \qquad j = 1,3,5,\ldots, \tag{1a}$$
$$m_j\ddot{x}_j + d\,\dot{x}_j + k\left(2x_j - x_{j+1} - x_{j-1}\right) - ax_j + bx_j^2 + cx_j^3 = 0 \qquad \forall \qquad j = 2,4,6,\ldots, \tag{1b}$$

where the constants a–c describe the nonlinear restoring force. Here, it is important to note that the coefficients of the restoring force model are related to several magnet parameters.

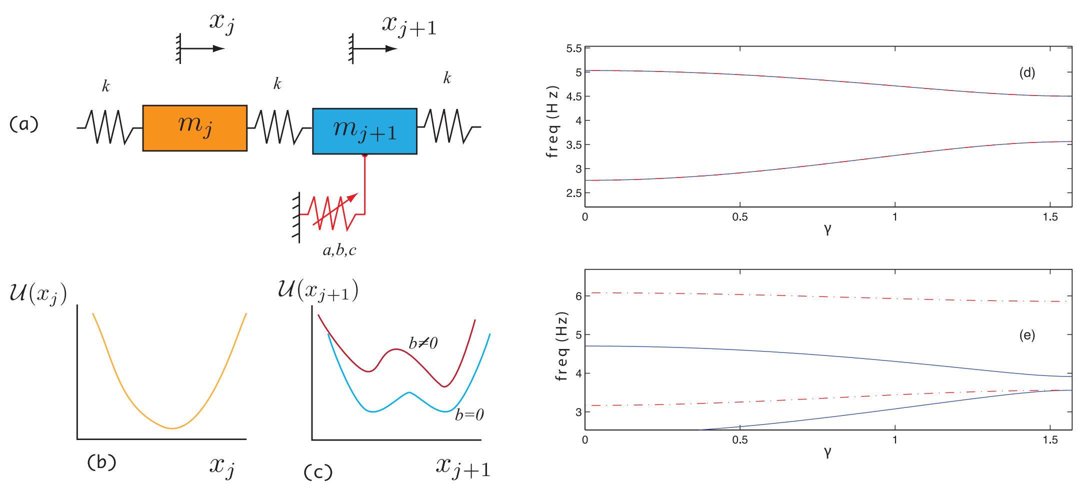

Figure 1: *Schematic diagram of a unit cell (a) comprised of two masses in an alternating pattern of a bistable (b) and monostable (c) oscillator. A bifurcation in the response of this system can be used to realize a different bandgap structure than the one found in the adjacent potential well - particularly when $b \neq 0$. Frequency band graphs show: (d) the symmetric case, where $b = 0$, and identical frequency band structures occur for each equilibria; (e) an asymmetric case, where $b \neq 0$, highlighting the pre-bifurcation bandpass region can be tailored to become a post-bifurcation bandgap region by tuning the parameter b.*

To explain the explain the behavior of this system, first consider the case of a symmetric potential, which requires $b = 0$ in Eq. (1b). After solving the nonlinear algebraic equations to find the system equilibria and expanding for small oscillations about the nonlinear equilibria, we solved for the frequency band structure that yields the bandgap region shown in Fig. 1(d); while Fig. 1(d) shows a bandgap occurs, the bandgap is identical for oscillations about either stable equilibria of the blue oscillator in Fig. 1(a). Similarly, one could say the bandgap structure is identical for the adjacent potential well owing to symmetry. In contrast to this case, consider what happens when symmetry is broken or equivalently when $b \neq 0$; the frequency band structure of Fig. 1(e) shows the bandgap regions for the adjacent well no longer coincide. This different bandgap structure is an important feature because a transition from one equilibria to another will shift the bandpass and filtered (or bandgap) regions by an amount proportional to the parameter b. However, a bifurcation is required to transition the oscillations about one stable equilibrium to oscillations about the neighboring stable equilibrium. For this example, we have used numerical simulations to demonstrate how the threshold for an escape from the shallower potential well (the 4-4.75 Hz bandgap region shown by the solid blue lines of Fig. 1e) can be used to transition the system to the deeper well (bandgap region shown by broken red lines of Fig. 1e) and quench the oscillation amplitude. This occurs only because the bandpass region of the shallower well was aligned with the bandgap region of the neighboring well. To summarize, successful demonstration of this concept will require simultaneous tailoring of the bifurcation transition and the bandgap structure.

This past year my group worked on both theoretically studying this phenomenon and developing an experimental system to demonstrate this behavior. Two papers were published on this topic - the first two references from the Journal Publications sections of this document. Basically, my group was successful in developing an experimental platform to demonstrate the phenomenon.

Students Supported

The students listed below have contributed to the research endeavors of this project:

- Brian Bernard, received a PhD in Aug 2014 and was supported by this project.

- Benjamin Owens, received a PhD in Aug 2014 and was supported by this project.

- Samuel Stanton, received a PhD in Mar 2011, was supported by a one year fellowship during his last year, but worked on several topics akin to the direction of the proposed research.

Past Interactions with ARL Researchers

We have worked with program director Samuel Stanton to identify an ARL research group with compatible interest. A student on this project, Ben Owens, interviewed with this group at Redstone Arsenal and was hired for the summer of 2012 at AMRDEC.

Honors

• *Philip E Doak Award* - Journal of Sound and Vibration. Awarded for the most cited journal article over a four year period.

• Elected Fellow of the American Society of Mechanical Engineers, Jan. 2013

• Selected for an endowed professorship. I was appointed as the Jeffrey N. Vinik Associate Professor of Mechanical Engineering and Materials Science as of July 1, 2012.

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Journal Publications

1. Bernard, B.P., Mazzoleni, M.J., Garraud, N., Arnold, D.P., Mann, B.P., 2014, "Experimental investigation of bifurcation induced bandgap reconfiguration," *Journal of Applied Physics*, – accepted, July 2014.
2. Tweeten, D.J., Mann, B.P., 2014, "Minimizing error in the logarithmic decrement method through uncertainty propagation," *Journal of Sound and Vibration*, V. 333, No. 13, pp. 2804-2811.
3. Mann, B.P., 2014, "Discussion: On the role of nonlinearities in vibratory energy harvesting: A Critical review and discussion," *Applied Mechanics Reviews*, V. 66, Issue 4, No. 040801.
4. Lipp, G.M., Mann, B.P., 2014, "Escape dynamics of an eccentric disk rolling on a curved surface," *Physica D Nonlinear Phenomena*, V. 266, pp. 34–41.

5. Tweten, D.J., Mann, B.P., 2013, "Delayed feedback control of chaos for arbitrary delays with the spectral element method," *International Journal of Dynamics and Control*, V. 1, pp. 283–289.

6. Bernard, B.P., Mann, B.P., 2013, "Passive band-gap reconfiguration born from bifurcation asymmetry," *Physical Review E*, V. 88, No. 052903, pp. 1-4.

7. Tweten, D.J., Mann, B.P., 2013, "On the use of weighting matrices to improve harmonic balance parameter identification results," *Journal of Sound and Vibration*, V. 332, No. 12, pp. 2941–2953.

8. Bernard, BP, Owens, BAM, Mann, B.P., 2013, "Uncertainty propagation in the bandgap structure of a 1D array of magnetically coupled oscillators," *Journal of Vibration and Acoustics*, V. 135, No. 041005, pp. 1–7.

9. Mann, B.P., Barton, D.A.W., Owens, B.A., 2012, "Uncertainty in performance for linear and nonlinear energy harvesting strategies," *Journal of Intelligent Material Systems and Structures*, V. 23, No. 13, pp. 1448-1457.

10. Stanton, S.C., Owens, B.A., Mann, B.P., 2012, "Harmonic balance analysis of the bistable piezoelectric inertial generator, " *Journal of Sound and Vibration*, V. 331, pp. 3617–3627.

11. Owens, B.A., Mann, B.P., 2012, "Linear and nonlinear electromagnetic coupling models in vibration-based energy harvesting," *Journal of Sound and Vibration*, V. 331, No. 4, pp. 922–937.

12. Sah, S.M., Mann, B.P., 2012, "Potential well metamorphosis of a pivoting fluid-filled container," *Physica D: Nonlinear Phenomena*, V. 241, No. 19, pp. 1660–1669.

13. Stanton, S.C., Owens, B.A., Mann, B.P., 2012, "Melnikov theoretic methods for characterizing the dynamics of the bistable piezoelectric inertial generator in complex spectral environments," *Physica D: Nonlinear Phenomena*, V. 241, No. 6, pp. 711–720.

14. Barton, D.A.W., Mann, B.P., Burrow, S.G., 2012, "Control-based continuation for investigating nonlinear experiments," *Journal of Vibration and Control*, V. 18, No. 4, pp. 509–520.

15. Stanton, S.C., Erturk, A., Mann, B.P., Dowell, E.H., Inman, D.J. 2012, "Nonlinear nonconservative behavior and modeling of piezoelectric energy harvesters including proof mass effects," Journal of Intelligent Material Systems and Structures, V. 23, No. 2, pp. 183–199.

16. Dunnmon, J.A., Stanton, S.C., Mann, B.P., Dowell, E.H., 2011, "On power extraction from aeroelastic limit cycle oscillations," *Journal Fluid Dynamics*, V. 27, No. 8. November 2011, pp. 1182–1198.

17. Sneller, A.J., Cette, P, Mann, B.P., 2011, "Experimental investigation of a post-buckled piezoelectric beam with an attached central mass used to harvest energy," *Journal of Systems and Control Engineering*, V. 225, No. 4, pp. 497–509.

18. Mann, B.P., Khasawneh, F.A., Fales, R., 2011, "Using information to generate derivative coordinates from noisy time series," *Communications in Nonlinear Science and Numerical Simulation*, V. 16, pp. 2999–3004.
19. Stanton, S.C., Erturk, A., Mann, B.P., Inman, D.J., 2010, "Resonant manifestation of intrinsic nonlinearity within electroelastic micropower generators," *Applied Physics Letters*, V. 97, No. 254101, pp. 1–3.
20. Stanton, S.C., Erturk, A., Mann, B.P., Inman, D.J., 2010, "Nonlinear piezoelectricity in electroelastic energy harvesters: Modeling and experimental identification," *Journal of Applied Physics*, V. 108, No. 074903, pp. 1–9.
21. Sneller, A.J., Mann, B.P., 2010, "On the nonlinear electromagnetic coupling between a coil and an oscillating magnet," *Journal of Physics D Applied Physics*, V. 43, No. 295005, pp. 1–10.
22. Stanton, S.A., Mann, B.P., 2010, "On the dynamic response of beams with multiple geometric or material discontinuities," *Mechanical Systems and Signal Processing*, V. 24, pp. 1409–1419.
23. Stanton, S.C., McGehee, C.C., Mann, B.P., 2010, "Nonlinear dynamics for broadband energy harvesting: Investigation of a bistable piezoelectric inertial generator," *Physica D Nonlinear Phenomena*, V. 239, pp. 640–653.
24. Mann, B.P., Owens, B.A. 2010, "Investigations of a nonlinear energy harvester with a bistable potential well," *Journal of Sound and Vibration*, V. 329, pp. 1215–1226.

Conference Publications

1. Mazzoleni, M.J., Krone, M.B., Mann, B.P., 2014, "Investigation of rocking semicircular and parabolic disk equilibria, stability, and natural frequencies," *Proceedings of the ASME Design Engineering Technical Conference*, Buffalo, NY, Aug. 17–20, paper no. IDETC2014-34396.
2. Bernard, B.P., Mann, B.P., 2013, "Energy absorption in a 1D array of axially aligned pendulums with linear torsional coupling," *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, San Diego, CA, Nov. 15–21, paper no. IMECE2013-64470.
3. Lipp, G.M., Hall, K.C., Mann, B.P., 2013,"Effect of rider position on bicycle stability," *Proceedings of ASME International Mechanical Engineering Congress and Exposition*, San Diego, CA, Nov. 15-21, paper no. IMECE2013-63809.
4. Ballard, Z., Mann, B.P., 2012, "Experimental study of human walking to running dynamics with application to energy harvesting," *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, Houston, TX, Nov. 9-15, paper no. IMECE2012-86276.

5. Owens, B.A.M., Stanton, S.C., Mann, B.P., 2012, ”Analysis of the bistable piezoelectric intertial generator by the harmonic balance method,” Proceedings of the ASME International Mechanical Engineering Congress and Exposition, Houston, TX, Nov. 9-15, paper no. IMECE2012-85965.

6. Lipp, G.M., Mann, B.P., 2012,“Potential Well Escape of an Eccentric Disk,” Proceedings of ASME International Mechanical Engineering Congress and Exposition, Houston, TX, Nov. 9-15, paper no. IMECE2012/85880.

7. Sah, S.M., McGehee, C.C., Mann, B.P., 2012, “Dynamics of a rocking horizontal pendulum under high frequency excitation,” *Proceedings of ASME Design Engineering Technical Conference*, Chicago, IL, Aug. 12-15, paper no. DETC2012-70877.

8. Bernard, B.P., Peyser, J.W., Mann, B.P., Arnold, D.P., 2012, “Using the mass ratio to induce bandgaps in a 1D array of nonlinearly coupled oscillators,” *Proceedings of ASME Design Engineering Technical Conference*, Chicago, IL, Aug. 12-15, paper no. DETC2012-70403.

9. Owens, B.A., Mann, B.P., 2012, “Fractal boundary explorations for a nonlinear two degree-of-freedom system,” *Proceedings of ASME Design Engineering Technical Conference*, Chicago, IL, Aug. 12-15, paper no. DETC2012/VIB-70327.

10. McGehee, C.C., Ballard, Z.C., Mann, B.P., 2011, “Potential well shaping through the use of impact barriers for broadband electroelastic energy harvesting,” *Proceedings of ASME Conference on Smart Materials, Adaptive Structures, and Intelligent Systems*, Scottsdale, AZ, Sep. 18-21, paper no. SMASIS2011-4972.

11. McGehee, C.C., Ballard, Z.C., Mann, B.P., 2011, “Horizontal pendulum with sudden changes in platform tilt,” *Proceedings of ASME Design Engineering Technical Conference*, Washington, D.C., Aug. 29-31, paper no. DETC2011/VIB-48423.

12. Owens, B.A., Sneller, A.J., Mann, B.P., 2011, “Comparison of linear and nonlinear electromagnetic coupling models for a linear oscillator,” *Proceedings of ASME Design Engineering Technical Conference*, Washington, D.C., Aug. 29-31, paper no. DETC2011/VIB-47782.

13. Dunman, J.A., Stanton, S.C., Mann, B.P., Dowell, E.H., 2011, “Aeroelastic limit cycles as a small scale energy source,” *Proceedings of ASME Design Engineering Technical Conference*, Washington, D.C., Aug. 29-31, paper no. DETC2011-47002.

14. Stanton, S.C., Erturk, A., Mann, B.P., Inman, D.J., 2010, “On the manifestation and influence of material nonlinearity in electroelastic power generator” ASME/AIAA Conference on Smart Materials, Adaptive Structures, and Intelligent Systems, Philadelphia, PA, Sep. 29–Oct. 1 ***(Best student paper for the entire conference)***.

Conference Abstracts

1. Barton, D.A.W., Mann, B.P., Burrow, S.G., “Investigation of nonlinear oscillators using control-based continuation,” *IUTAM Symposium*, Aberdeen, UK, Jul. 27–30, 2010.

Select Technical Presentations

1. Mann, B.P., "Energy harvesting with nonlinear phenomena," invited seminar for at University of Freiburg, Freiburg, Germany, Aug 2013.
2. Mann, B.P., "Energy harvesting with nonlinear phenomena," invited special talk for ASME SMASIS conference, Stone Mountain, GA, Sep. 19-21, 2012.
3. Mann, B.P., "Strategies for broadband energy harvesting," invited speaker for the Young Researchers Transatlantic Academy, Jun. 3-7, 2012, RWTH Aachen, Germany.
4. Mann, B.,P., " Opportunities for fundamental advancements in energy harvesting," ARO Workshop on revolutionary research in energy harvesting, Austin, TX, April 7, 2011.
5. Mann, B.P., "Energy harvesting with nonlinear phenomena," Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA Oct. 28, 2010.